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Effect of Water on Piloted Ignition of Cellulosic Materials

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Prepared for
U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
(formerly National Bureau of Standards)
Center for Fire Research
Gaithersburg, MD 20899

**U.S. DEPARTMENT OF COMMERCE
C. William Verity, Secretary
NATIONAL INSTITUTE OF STANDARDS
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Ernest Ambler, Director**

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**EFFECT OF WATER ON PILOTED IGNITION OF
CELLULOSIC MATERIALS**

ANNUAL PROGRESS REPORT

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September, 1987

Prepared by

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Fire Growth and Extinction

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A THEORETICAL STUDY OF ONE-DIMENSIONAL PILOTED IGNITION

A THEORETICAL STUDY OF ONE-DIMENSIONAL PILOTED IGNITION

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ABSTRACT

This paper presents a simple theoretical model of the piloted ignition process. The two-dimensional coupled solid and gas phase problem is simplified by assuming that the mass evolution rate from the combustible solid is a known function of time and by employing a plane rather than a point ignition source. These assumptions reduce the model problem to a transient one-dimensional analysis of the gas-phase phenomena. The model equations are solved numerically using a fast scheme especially suited to combustion problems. The pilot flame is modeled as a thin slab of gas that is periodically heated to the adiabatic flame temperature of the stoichiometric mixture. The effects of: (i) the location of the ignition source, (ii) the fuel mass evolution rate from the surface, and (iii) the surface temperature of the solid are investigated. This model adequately explains the pre-ignition flashes that are often observed experimentally. It also provides a rational criterion for positioning of the pilot flame. It is found that the minimum fuel flow rate, by itself is insufficient for predicting the onset of piloted ignition and that heat losses to the surface play an important role. Also, the conditions at extinction of a steady diffusion flame are found to be identical to those at piloted ignition.

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NOMENCLATURE

A Pre-exponential factor

C_p Specific heat

D Damkohler number, $D = \frac{A \rho^2 C_p h^2}{\lambda} e^{-\beta^\circ}$

E Activation energy

h Boundary layer thickness

Le Lewis number, $Le = \lambda / \rho C_p D$

m Mass flux, $m = \rho v$

M Nondimensional mass flux, $M = m C_p h / \lambda$

q Heat release

Q Nondimensional heat release, $Q = q / C_p (T_f - T_\infty)$

R Ideal gas constant

R Nondimensional reaction term, $R = D Y_o Y_F \exp \left[\frac{-\beta(1-\theta)}{1 - \alpha^\circ(1-\theta)} \right]$

t Time

T Temperature

v Velocity

x Position coordinate

Greek

α° Nondimensional factor, $\alpha^\circ = 1 - T_\infty / T_f$

β Nondimensional activation energy, $\beta = \beta^\circ \alpha^\circ$

β° Nondimensional activation energy, $\beta^\circ = E / RT_f$

δ Laminar flame thickness, $\delta \sim \lambda / \rho_o v_o C_p$

Θ Nondimensional temperature, $\Theta = (T - T_\infty) / (T_f - T_\infty)$

λ Thermal conductivity

ν Stoichiometric coefficient

ξ Nondimensional position coordinate, $\xi = x/h$

ρ Density

ρ Density

τ Nondimensional time, $\tau = \lambda t / \rho C_p h^2$

Subscripts

f Flame

F Fuel

i Ignition source

o Oxygen

s Surface

∞ Ambient

A THEORETICAL STUDY OF ONE-DIMENSIONAL PILOTED IGNITION

1. INTRODUCTION

The problem of piloted ignition of combustible materials under external heating is fundamental to fire science and technology because it addresses the basic issues of fire initiation and growth. Its importance is further underscored by the numerous investigations that have been conducted to date. References 1-4 serve as an excellent review of this previous work. The phenomenon of piloted ignition, however, remains rather poorly understood. This is evident from the empirical ignition criteria that have been proposed in the literature. Some of these are: critical surface temperature, critical fuel mass flux, critical char depth and critical mean solid temperature. Of these, critical fuel mass flux at ignition appears physically the most reasonable, but critical surface temperature has proved to be the most useful, since it can be easily related to flame spread. It is evident that a clear understanding of the piloted ignition process is essential for fire research. In this paper an attempt has been made to develop this understanding.

The physical mechanism of piloted ignition is quite complex. The solid must first chemically decompose to inject fuel gases into the surrounding air. The fuel then mixes with the oxygen to produce a flammable mixture in the boundary layer which is ignited by an ignition source. A plausible physical configuration of this process is illustrated in Figure 1.

In the early stages of solid pyrolysis, the fuel flow rate is very small and the fuel-air mixture in the boundary layer is not combustible. As the fuel flow rate increases with time this mixture becomes rich enough to

allow a pre-mixed flame to propagate through the boundary layer. This pre-mixed flame consumes nearly all the available fuel and it is then quenched by heat loss to the surface, unless the fuel flow rate is large enough to replenish the consumed fuel. Thus, depending on the fuel flow rate, either a flash (a quenched pre-mixed flame) or a sustained diffusion flame (piloted ignition) is observed. Experimental observations of this phenomena are shown in Figure 2. The momentary rise in surface temperature prior to sustained ignition is due to the flashes.

From the experimental observations, it is clear that the piloted ignition process involves both pre-mixed and diffusion flames. Also, the true criterion for sustained piloted ignition is determined by the conditions that allow the conversion of a pre-mixed flame to a diffusion flame. These conditions include the fuel flow rate and the surface temperature that determines the heat losses responsible for quenching the pre-mixed flame.

A complete theoretical model of the piloted ignition process must include transient analysis of: (i) thermal decomposition of the solid to produce fuel gases, (ii) mixing of fuel and air in the two-dimensional boundary layer, (iii) pre-mixed flame propagation originating from the ignition source, (iv) quenching of this pre-mixed flame by heat losses to the surface, and (v) establishment of a sustained diffusion flame in the boundary layer. This rather formidable problem is simplified by assuming that the solid-phase thermal response to the applied heat flux is a known function of time and by employing a plane rather than a point ignition source. These assumptions reduce the problem to a transient one-dimensional analysis of the gas-phase phenomena. Thus capturing the bare essentials of the piloted ignition process.

2. MATHEMATICAL MODEL OF ONE-DIMENSIONAL PILOTED IGNITION

A schematic of the model problem is shown in Figure 3. A gas stream containing the fuel is fed uniformly and at a constant rate through a porous plate whose surface temperature is assumed constant. Condition at a distance 'h' above the plate are maintained constant by a fast flowing oxidizer stream. A plane ignition source (whose distance from the plate, $0 < x_1 < h$, is variable) is placed near the porous plate. This ignition source is periodically "turned on" to test for piloted ignition. The chemical reaction is assumed to be a simple second-order, one-step irreversible Arrhenious-type.



The governing energy and species equations are:

$$\rho \frac{\partial T}{\partial t} + \rho v \frac{\partial T}{\partial x} = \frac{\partial}{\partial x} \left(\frac{\lambda}{C_p} \frac{\partial T}{\partial x} \right) + q \frac{A}{C_p} \rho^2 Y_F Y_O e^{-E/RT}, \quad (2)$$

$$\rho \frac{\partial Y_F}{\partial t} + \rho v \frac{\partial Y_F}{\partial x} = \frac{\partial}{\partial x} \left(\rho D \frac{\partial Y_F}{\partial x} \right) - A \rho^2 Y_F Y_O e^{-E/RT}, \quad (3)$$

and

$$\rho \frac{\partial Y_O}{\partial t} + \rho v \frac{\partial Y_O}{\partial x} = \frac{\partial}{\partial x} \left(\rho D \frac{\partial Y_O}{\partial x} \right) - \nu A \rho^2 Y_F Y_O e^{-E/RT}, \quad (4)$$

and the initial and boundary condition are:

at $t = 0$, $0 < x < h$;

$$Y_F = 0, Y_O = Y_{O\infty}, \text{ and } T = T_\infty, \quad (5)$$

$$\text{at } x = 0, t > 0; \quad \rho D \frac{\partial Y_F}{\partial x} = \rho v (Y_F - Y_{FS}),$$

$$\rho D \frac{\partial Y_O}{\partial x} = \rho v Y_O, \quad (6)$$

$$T = T_s$$

and at $x = h$, $t > 0$;

$$Y_F = 0; Y_O = Y_{O\infty}; T = T_\infty. \quad (7)$$

In order to simplify these equations, ρ is assumed to be a constant (implying that $m = \rho v$ is not a function of x ; thus, mass conservation is automatically satisfied). Also, λ , C_p and D are assumed to be constants.

The above equations are non-dimensionalized as follows:

$$\xi = \frac{x}{h}; \quad \tau = \frac{\lambda t}{\rho C_p h^2}; \quad M = \frac{m C_p h}{\lambda}$$

$$\theta = \frac{T - T_\infty}{T_f - T_\infty}; \quad D = \frac{A \rho^2 C_p h^2}{\lambda} e^{-\beta^\circ} \quad (8)$$

$$\beta^\circ = \frac{E}{RT_f} \quad ; \quad Q = \frac{q}{C_p (T_f - T_\infty)} \quad ; \quad \beta = \beta^\circ \alpha^\circ$$

$$\alpha^\circ = 1 - T_\infty/T_f \quad ;$$

and with the definitions

$$L \{ \cdot \} = \frac{\partial(\cdot)}{\partial \tau} + M \frac{\partial(\cdot)}{\partial \xi} - \frac{\partial^2(\cdot)}{\partial \xi^2} \quad ,$$

and

$$R = D Y_F Y_O \exp \left[\frac{-\beta(1 - \theta)}{1 - \alpha^\circ(1 - \theta)} \right] \quad ,$$

the governing equations may be re-written as:

$$L \begin{Bmatrix} \theta \\ Y_F \\ Y_O \end{Bmatrix} = \begin{Bmatrix} Q \\ -1 \\ -\nu \end{Bmatrix} R. \quad (9)$$

The initial and boundary conditions become:

at $\tau = 0$; $0 < \xi < 1$:

$$\theta = 0; \quad Y_F = 0; \quad Y_O = Y_{O\infty} \quad , \quad (10)$$

at $\xi = 0$; $\tau > 0$: $\theta = \theta_s$,

$$\frac{\partial Y_F}{\partial \xi} = M(Y_F - Y_{FS}) \quad , \quad (11)$$

$$\frac{\partial Y_O}{\partial \xi} = M Y_O \quad ,$$

and at $\xi = 1$; $\tau \geq 0$

$$\theta = 0; \quad Y_F = 0; \quad Y_O = Y_{O\infty} . \quad (12)$$

The governing Equations (9) along with the initial and boundary conditions are solved numerically by using a finite difference formulation.

3. NUMERICAL SOLUTION

A non-uniform grid is used for the numerical computations. As shown in Figure 4, this grid is closely spaced around the ignition source to ensure satisfactory resolution for the pre-mixed flame propagation. An efficient numerical method that splits the solution procedure into a homogeneous reaction calculation and a subsequent convective-diffusive calculation was developed. This numerical procedure is described in Reference 6.

3.1 Pre-mixed Flame Velocity Calculations

First, the pre-mixed flame velocity was calculated in order to: (i) adjust the input parameters, (ii) verify the numerical code, (iii) determine an appropriate grid spacing and time step, and (iv) determine the input energy needed for the ignition source. For these calculations, the fuel is assumed to be methane and essentially the input parameters given by Coffee [7] were used. However, the reaction order used in Reference (7) is 3 as opposed to 2 for the present problem. Thus, the pre-exponential factor, A, was slightly modified to obtain the same steady-state pre-mixed flame velocity in a stoichiometric mixture. These input parameters are:

$$E = 29.1 \text{ Kcal/mole}; T_f = 2230^\circ\text{K}; T_\infty = 298^\circ\text{K}; \nu = 4; q = 11355 \text{ cal/gm fuel.}$$

$$C_p = 0.323 \text{ cal/gm}^\circ\text{K}; \lambda = 1.5 \times 10^{-4} \text{ cal/cm}^\circ\text{K sec}; \rho = 3.74 \times 10^{-4} \text{ gm/cm}^3$$

$$Le = \frac{\lambda}{\rho C_p D} = 1 \text{ and } \rho A = 3.56 \times 10^9/\text{sec.}$$

The pre-mixed flame velocity calculations were performed by using the numerical code developed to solve the governing Equations (9), with the initial and boundary conditions modified as follows: (i) Initially a stoichiometric mixture of methane and air is assumed to exist above the solid surface and the fuel flow rate from the surface is set equal to zero (i.e., $m = 0$). Thus, $Y_F(0, x) = 0.0546$ and $Y_O(0, x) = 0.219$. (ii) The surface temperature is assumed to be equal to the adiabatic flame temperature, i.e. $\theta = \theta_s = 1$.

Thus, the pre-mixed mixture is ignited at the surface and the flame propagates toward the outer boundary, eventually attaining a steady speed. This steady-state flame velocity is determined by noting the propagation rate of the temperature profile and by assuming the densities of the burned and the unburned gas mixtures to be identical. A uniform grid was employed for these calculations and different grid spacings and time steps were investigated. The results of these calculations are summarized in Table 1, which shows that the calculated steady-state flame velocity is very close to other calculations, as well as, to the experimental result. Thus, validating the numerical code and the input data.

The grid spacing and the time step for the piloted ignition calculations is determined from Table 1. This table shows that a grid spacing of $\Delta\xi = 3.7 \times 10^{-3}$ provides a sufficient resolution. This non-dimensional grid spacing corresponds to an actual physical spacing of 0.055 mm, which is smaller than the flame thickness. The flame thickness is estimated by using [5] $\delta \approx \lambda / C_p \rho_o v_o$, where ρ_o and v_o are the unburned

mixture density and velocity respectively. This calculation results in a pre-mixed flame thickness of 0.092 mm. A finer grid was not used to cut down on the CPU time. Since, the pre-mixed flame propagation speed is not the desired final result of the piloted ignition problem, the largest time step shown in Table 1 ($\Delta\tau = 2.7 \times 10^{-5}$) is used to save CPU time. Also, twice this time step ($\Delta\tau = 5.4 \times 10^{-4}$) was used prior to "turning on" the ignition source.

3.2 Numerical Simulation of the Ignition Source

In the numerical code, the ignition source is "turned on" by simply raising the temperature of a slab of gas to the adiabatic flame temperature. The thickness of this slab is chosen to be three grid spaces, which is approximately twice the pre-mixed flame thickness. Choice of this thickness is based on the observation [5] that "Ignition will occur only if enough energy is added to the gas to heat a slab about as thick as a steadily propagating adiabatic laminar flame to the adiabatic flame temperature." The reason for choosing an ignition source thickness larger than the pre-mixed flame thickness is that the gas mixture is not stoichiometric. Thus, the chosen thickness ensures ignition if the fuel/air mixture in the boundary layer has reached its lean flammability limit.

It is important that the amount of energy added to the system by the ignition source be minimized. Thus, the pilot cannot be left "turned on" all the time. This is especially critical because a plane rather than a point ignition source is used to render the model problem one-dimensional. To overcome this difficulty a novel method has been devised. When the ignition source is "turned on" the data for temperature and species is placed into a temporary file. After calculating for several time steps the occurrence of ignition is determined by observing the development of the

temperature and species profiles. If ignition is not observed, then the data from the temporary file is recalled and the calculation is re-started at that point. This procedure eliminates any accumulation of energy from periodic trials prior to the occurrence of piloted ignition.

3.3 Steady-State Diffusion Flame Calculations

In the latter stages of piloted ignition, the premixed flame develops into a diffusion flame, which slowly moves toward its steady-state location. The governing equations and the boundary conditions describing this steady diffusion flame are simply the steady-state version of the Equations (9), (11) and (12). Thus, the location of the steady diffusion flame and the corresponding temperature and species concentrations may be found either from the large time solution of the time dependent Equations (9), (11) and (12) (i.e., in the later stages of piloted ignition) or by directly solving the steady-state versions of Equation (9), (11) and (12). It may also be obtained analytically in the thin flame sheet Burke-Schumann limit. The analytical solution [Reference 8] yields the diffusion flame location as:

$$x_F = 1 - \frac{1}{M} \ln \left\{ 1 + \frac{Y_{O\infty}}{\nu Y_{FS}} \right\} \quad (13)$$

Table 2 shows a comparison of the diffusion flame location calculated by all three methods. The transient piloted ignition calculations were terminated after about 4 seconds (elapsed real time) because changes in the diffusion flame location had become very slow. In these calculations the surface temperature of the solid was assumed to be 298°K and the ignition source was located at the minimum distance from the

surface. (This minimum distance for the ignition source will be discussed later.)

Numerical solution of the steady-state versions of the Equations (9), (11) and (12) was obtained by the iteration method. Calculations were started by guessing the location of the diffusion flame and the corresponding temperature and species profiles. Using this initial guess, the non-linear reaction rate term (R ; See Equation (9)) was calculated and then the energy and species equations were solved to obtain a new set of conditions. This iteration was performed until the solution converged to within a prescribed error.

It is evident from Table 2 that the results of all three calculations compare quite satisfactorily. These calculations further confirm the validity of the numerical code for the piloted ignition calculations.

4. RESULTS AND DISCUSSION

After verifying the piloted ignition model for the limiting cases of pre-mixed flame propagation (the early stage) and development of a steady-state diffusion flame (the later stage), several aspects of the piloted ignition process were investigated. In this investigation the fuel concentration in the solid phase was taken as unity ($Y_{FS} = 1$), and unless otherwise specified, the solid surface temperature was T_∞ ($T_S = T_\infty = 298^\circ\text{K}$). Various case studies are summarized below:

4.1 Piloted Ignition Phenomena

To investigate the details of the piloted ignition process, the following conditions were assumed: $h = 1.5$ cm; $m = 8.34 \times 10^{-5}$ gm/cm² sec; $T_S = 298^\circ\text{K}$; $Y_{FS} = 1$; and the ignition source is placed at $x_i = 1.186$ cm (which corresponds to the theoretical location of the steady diffusion flame).

Note that in the actual experiment both surface temperature and fuel mass flux will increase with time as the solid is heated by a constant heat flux. Also, the fuel concentration in the solid is typically less than 100% (i.e., $Y_{FS} < 1$) due to the presence of moisture. Thus, the calculated time for piloted ignition cannot be compared with experiments. However, the gas-phase ignition process (which is the focus of this study) is not expected to be different. Furthermore, in the numerical model, it is fairly straight forward to assign the experimentally measured values of m , T_S and Y_{FS} when they become available.

Figures 5 and 6 show the results of piloted ignition calculations. The mixture was ignited at $t = 1.089$ seconds, as can be seen by the sharp temperature peak and corresponding dips in the fuel and oxidizer concentrations. The pre-mixed flame then travels quickly into the unburnt mixture in both direction i.e., toward the porous plate and away from the porous plate. This can be seen more clearly from the heat flux profiles (which are proportional to the temperature gradient) shown in Figure 6. At $t = 1.102$ seconds (i.e. 13 milliseconds later) the pre-mixed flame has consumed nearly all the available oxygen on the fuel side and all the available fuel on the oxidizer side of the ignition source -- thus, establishing conditions that are appropriate for the formation of a diffusion flame. At this time the surface experiences a large heat flux (see curve (3) in Figure 6), which is probably responsible for the sharp momentary rise in temperature observed during the experiment shown in Figure 2. Note that during the pre-mixed flame stage the heat flux is very large. However, once the flame converts into a diffusion flame the magnitude of the heat flux drops sharply.

At times larger than 1.102 seconds, the temperature, fuel and oxygen concentrations slowly adjust to those for a steady state diffusion flame. Finally, at $t \approx 4$ seconds a steady-state diffusion flame is established.

Note that the final location of the steady-state diffusion flame is nearly identical to that of the ignition source ($\xi \approx 0.8$). This is because the ignition source was placed at the theoretically calculated diffusion flame location (Table 2).

4.2 Quenching of the Pre-mixed Flame (Flashes)

If the ignition source is too close to the cold porous wall (or the sample surface) then thermal quenching of the pre-mixed flame prevents the development of a diffusion flame and hence the occurrence of piloted ignition, resulting in a flash. Similar behavior is observed if the fuel flow rate is lower than the lean flammability limit. This is discussed in the next Section. In the case discussed here, the fuel flow rate is the same as that for the case in Section 4.1, but the ignition source is placed closer to the surface (i.e., at $x_i = 0.193$ cm, as compared with $x_i = 1.186$ cm for the previous case). For this case, the gas ignites at 0.1 seconds (much smaller than 1.089 seconds for the previous case) but the ignition is not sustained.

Figures 7,8,9 and 10 show respectively the temperature, fuel concentration, oxygen concentration and the heat flux profiles during this momentary flaming. It can be seen that nearly all of the oxygen on the fuel side and the fuel on the oxygen side are consumed, but the temperature eventually decays and the fuel and oxygen are replenished.

It is interesting to note that the fuel concentrations at the location of the ignition source for both this and the previous case are nearly the same ($Y_F = 0.0418$ for the present case and $Y_F = 0.0414$ for the previous case) and yet sustained ignition was not achieved. Table 3 also shows the fuel concentration at the location of the ignition source and at the time of piloted ignition for different fuel flow rates and ignition source locations. Note that the value of Y_F is remarkably constant (average

is 0.0445) despite the fact that in many cases the flame was quenched. This value of Y_F is approximately 80% of the stoichiometric mass fraction and is about 1.74 times the stated lean flammability limit for CH_4 [Ref. 8]. The reason for the difference between the lean flammability limit and Y_F at ignition is not clear to the authors. It may be because of the assumption of one-step chemistry or because of the difference in the initial and boundary conditions that were used. However, it is clear that piloted ignition cannot be predicted solely on the basis of the lean flammability limit and that heat losses to the solid surface play a very important role.

4.3 Minimum Fuel Flow Rate for Piloted Ignition

In this case the fuel flow rate was reduced to 3.128×10^{-5} gm/cm² sec which is slightly less than the minimum fuel flow rate listed in Table 3 (3.34×10^{-5} gm/cm² sec) for which piloted ignition was possible. Note that this fuel flow rate is roughly one-third the fuel flow rate used in the previous two cases. Here, regardless of the location of the ignition source, a sustained diffusion flame was not obtained.

Figures 11 through 14 show the temperature, fuel concentration, oxygen concentration and heat flux profiles during flashes caused by the low fuel flow rate. For the results presented in these figures, the ignition source was located at 0.67 cm from the surface which corresponds to the theoretical location of the steady diffusion flame. It can be seen that although most of the oxygen on the fuel side and the fuel on the oxygen side are consumed by the pre-mixed flame, the fuel supply rate is too low to enable the establishment of a diffusion flame. Hence, the temperature quickly falls to its ambient value. A comparison of Figures 8 and 12 shows how slowly the fuel is replenished. In Figure 8, the fuel concentration at the surface recovers to about 75% of its initial value in 0.1 seconds,

whereas, in Figure 12 the fuel concentration at the surface recovers to only about 50% of its original value in 0.5 seconds.

Since for successful piloted ignition it is necessary to establish a steady diffusion flame, the minimum fuel flow rate at extinction of the steady diffusion flame is expected to be identical to that required for piloted ignition. The minimum fuel flow rate at extinction is determined by numerically solving the steady-state version of the governing Equation (9). For this calculation the temperature and species profiles are first calculated for the conditions for which the steady diffusion flame is known to exist. These results are then used as an initial guess for subsequent calculations with slightly lower fuel flow rate. This procedure is continued until the temperature and species profiles are the same as those with no chemical reaction, i.e., no diffusion flame exists. This rather stringent condition for extinction produces a lower bound for the fuel flow rates.

By using the above procedure the minimum fuel flow rate at extinction is found to be 2.88×10^{-5} gm/cm² sec. This fuel flow rate is only 8% lower than the minimum fuel flow rate for piloted ignition (3.128×10^{-5} gm/cm² sec). This result seems to substantiate the hypothesis that conditions at extinction of a steady diffusion flame are identical to those at piloted ignition. This hypothesis was used in Reference [4] to obtain an approximate analytical solution for the piloted ignition problem.

All results presented thus far assume that the surface temperature of the solid is held constant at T_{∞} (i.e., $T_s = T_{\infty} = 298^{\circ}\text{K}$). As T_s is increased, heat losses to the surface are decreased which are expected to reduce the minimum fuel flow rate required for the establishment of a steady diffusion flame and for sustained piloted ignition. Calculations with $T_s = 491^{\circ}\text{K}$ show that the minimum fuel flow rate at extinction of a diffusion flame reduces to 2.43×10^{-5} gm/cm² sec and that for sustained piloted

ignition reduces to 2.71×10^{-5} gm/cm² sec. Once again, the fuel flow rate at extinction of a diffusion flame is about 10% lower than for sustained piloted ignition.

4.4 Location of the Ignition Source

As noted in Section 4.2, the location of the ignition source is very important in determining whether or not sustained piloted ignition will occur. This fact was experimentally observed by Simms [9], who states: "The pilot ignition time depends not only upon the intensity of radiation and the density of wood, but also upon the position and possibly upon the size of the pilot flame as well."

Table 3 summarizes the calculations for different locations of the ignition source at a given fuel flow rate. It can be seen that there exists a minimum location of the ignition source for sustained piloted ignition regardless of the fuel flow rate. For ignition source distances lower than the minimum location, the flame is quenched (see Section 4.2). As the fuel flow rate is decreased, the minimum location approaches the theoretical location of the steady-state diffusion flame. Thus, the optimum location of the pilot is the location of the steady-state diffusion flame which can be estimated from Equation (13). Note that in the actual experiment, the fuel flow rate and surface temperature slowly increases as the solid is exposed to a given external radiation. Thus, to find the minimum time (or fuel flow rate) at which sustained ignition occurs, the pilot must be located at the eventual position of steady diffusion flame.

As the surface temperature increases both the minimum fuel flow rate for sustained piloted ignition and the minimum distance of the ignition source decreases. Table 4 shows the minimum distance of the ignition source at a surface temperature of 491°K. A comparison of Tables (3) and (4) shows that the minimum distance has been considerably reduced with increase in

surface temperature. In actual experiments where the surface temperature increases with the time of exposure to external radiation, an incorrect placement of the ignition source will eventually result in ignition, but at a higher surface temperature and at a longer ignition delay time. This may partially explain the wide range (300 to 540°C) of measured surface temperature for piloted ignition of wood that have been reported in the literature.

5. CONCLUSIONS

The simple one-dimensional numerical model presented here reveals the basic structure of the piloted ignition process. In the early stages of piloted ignition a pre-mixed flame quickly propagates through the unburned mixture consuming nearly all the fuel on the oxidizer side and all the oxygen on the fuel side, thus establishing conditions that are appropriate for the formation of a diffusion flame. This pre-mixed flame may be quenched (resulting in a flash) if the fuel flow rate is too low or if the ignition source is too close to the surface (due to excessive heat losses). Under appropriate conditions a diffusion flame is established which slowly moves toward the steady-state diffusion flame location. It has been found that the minimum fuel flow rate in itself is not sufficient to predict the onset of sustained piloted ignition (as is often cited in the literature) and that heat losses to the solid surface play an important role. These calculations also confirm the hypothesis that the conditions at extinction of a steady diffusion flame are very nearly the same as those required for piloted ignition.

The optimum location of the pilot flame for actual experiments is found to be the eventual location of the steady diffusion flame. As expected, both the optimum location of the pilot flame and the minimum fuel

flow rate required for piloted ignition decreased with increase in surface temperature. This analysis also confirms that the sharp rise in surface temperature observed during the experiments (flashes in Figure 2) is due to burnout of the accumulated fuel during the pre-mixed flame propagation stage. Note, that during the pre-mixed flame propagation stage the heat flux is an order of magnitude larger than in the steady diffusion flame stage.

6. ACKNOWLEDGEMENTS

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TABLE 1: Flame velocities calculated by using different grid spacing and time steps. (units: cm/sec)

$\Delta\tau$					
$\Delta\xi$	2.7×10^{-7}	5.4×10^{-7}	2.7×10^{-6}	5.4×10^{-6}	2.7×10^{-5}
7.4×10^{-4}	38.2	38.3	37.3	36.2	7.4
1.5×10^{-3}	38.2	38.2	37.2	36.1	26.0
3.7×10^{-3}	37.5	37.3	36.5	35.4	25.7

NOTE: Coffee's calculations [Ref. 7]--39.8 cm/sec
 Estimated from analytical formula [Ref. 5]--39.18 cm/sec
 Experimental measurements [Ref. 8]--37.3 cm/sec

TABLE 2: Steady State Diffusion Flame Location (x_F)

Fuel flow rate (gm/cm ² sec)	x_F from transient calculations after 4 sec (cm)	x_F from steady-state calculation (cm)	x_F from Equation (13) analytical (cm)	Flame temperature	
				Numerical (°K)	Analytical (°K)
2.5×10^{-4}	1.385	1.384	1.396	2115	2137
8.34×10^{-5}	1.175	1.174	1.186	1840	1868
4.17×10^{-5}	0.866	0.866	0.878	1396	1458
3.75×10^{-5}	0.800	0.800	0.809	1292	1367
3.34×10^{-5}	0.724	0.684	0.723	1109	1253

TABLE 3: Location of the Ignition Source and the Fuel Concentration at this location. All calculations are for $T_s = T_\infty = 298^\circ\text{K}$

Fuel flow rate (gm/cm ² sec)	Location of the ignition source (cm)	Y_F at the ignition source location and at the time of ignition	Time elapsed for piloted ignition (sec)	Observations
8.34×10^{-5}	1.186 ⁺	4.14×10^{-2}	1.089	ignition
	0.555	4.57×10^{-2}	0.279	ignition
	0.280	4.34×10^{-2}	0.141	ignition
	0.204*	4.31×10^{-2}	0.106	ignition
	0.170	4.18×10^{-2}	---	flame quenched
4.17×10^{-5}	0.874 ⁺	4.48×10^{-2}	1.299	ignition
	0.555	4.49×10^{-2}	0.609	ignition
	0.397*	4.48×10^{-2}	0.457	ignition
	0.390	4.51×10^{-2}	---	flame quenched
	0.280	4.51×10^{-2}	---	flame quenched
3.75×10^{-5}	0.800 ⁺	4.49×10^{-2}	1.289	ignition
	0.555	4.49×10^{-2}	0.709	ignition
	0.540*	4.50×10^{-2}	0.691	ignition
	0.445	4.51×10^{-2}	---	flame quenched
	0.280	4.51×10^{-2}	---	flame quenched
3.34×10^{-5}	0.724 ⁺	4.48×10^{-2}	1.410	ignition
	0.718*	4.48×10^{-2}	1.358	ignition
	0.710	4.48×10^{-2}	---	flame quenched
	0.555	4.50×10^{-2}	---	flame quenched
	0.280	4.49×10^{-2}	---	flame quenched
3.13×10^{-5}	No sustained diffusion flame regardless of the location of the ignition source.			

+ Location of the steady-state diffusion flame.

* Minimum location of the ignition source for sustained flaming (piloted ignition).

TABLE 4: Minimum Distance of the Ignition Source at a Surface Temperature of 491°K.

Fuel flow rate (gm/cm ² sec)	Minimum location of the ignition source (cm)
8.34 x 10 ⁻⁵	0.181
4.17 x 10 ⁻⁵	0.225
3.75 x 10 ⁻⁵	0.230
3.34 x 10 ⁻⁵	0.302
3.13 x 10 ⁻⁵	0.538
2.92 x 10 ⁻⁵	0.665

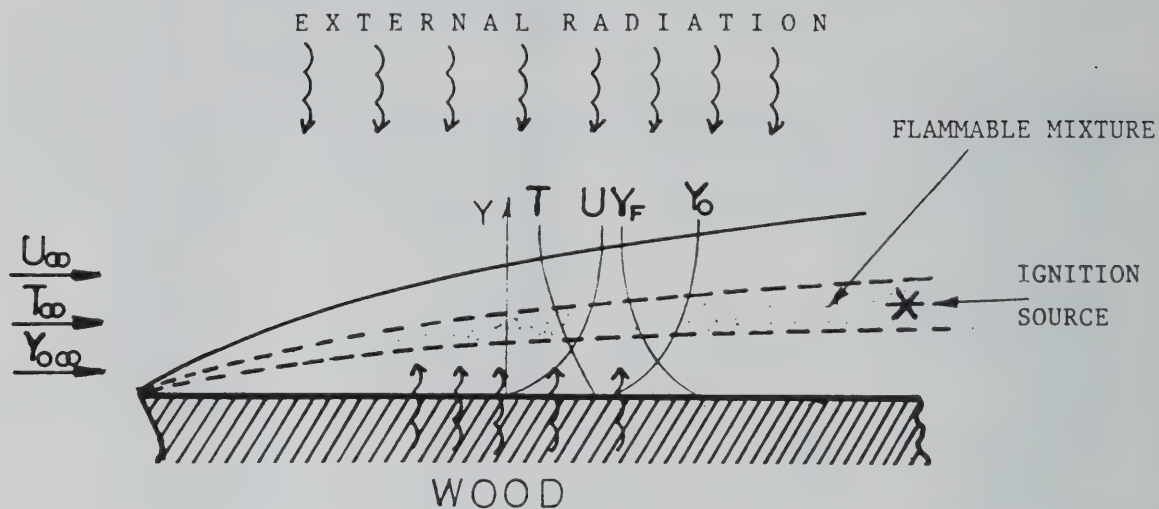


FIGURE 1. Piloted ignition of solids -- The physical problem.

Edge of the boundary layer; $Y_O = Y_O$; $X = h$ $X = h$

PLANE IGNITION SOURCE $X = X_i$

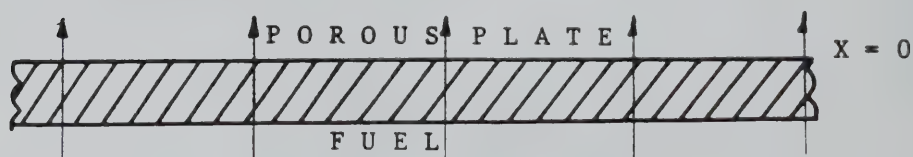


FIGURE 3. Piloted ignition of solids -- The model problem.

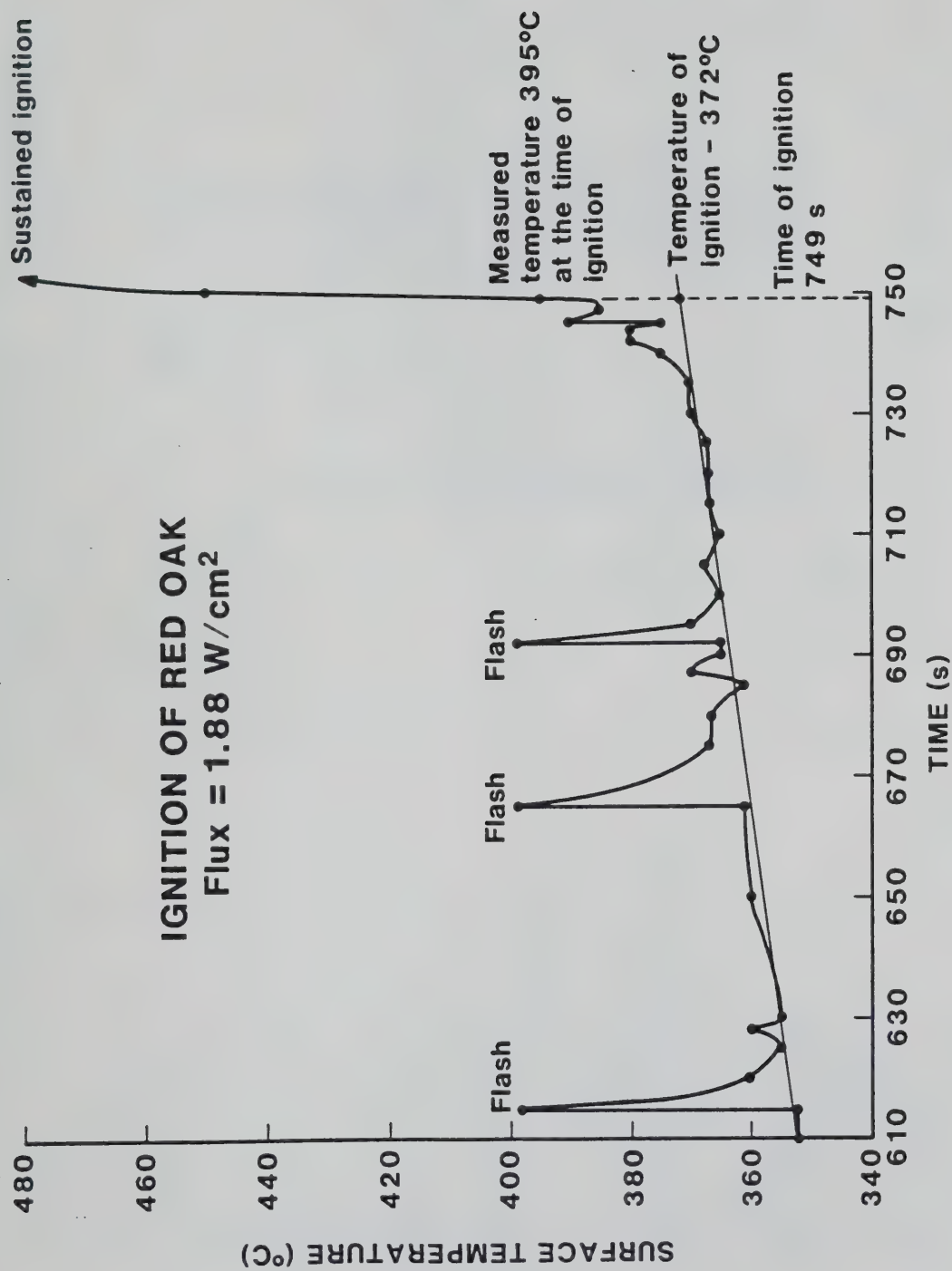


FIGURE 2: Surface temperature-time history during piloted ignition of a red oak sample.

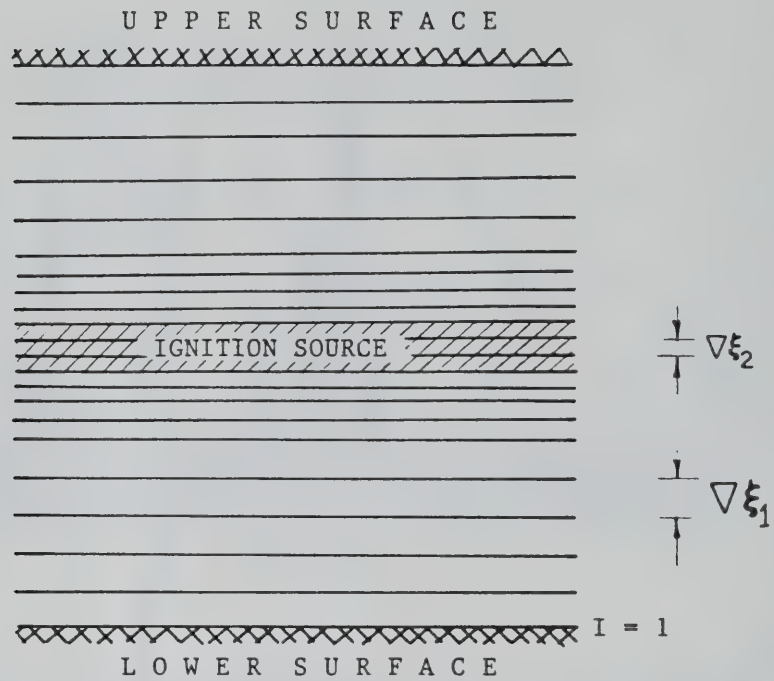
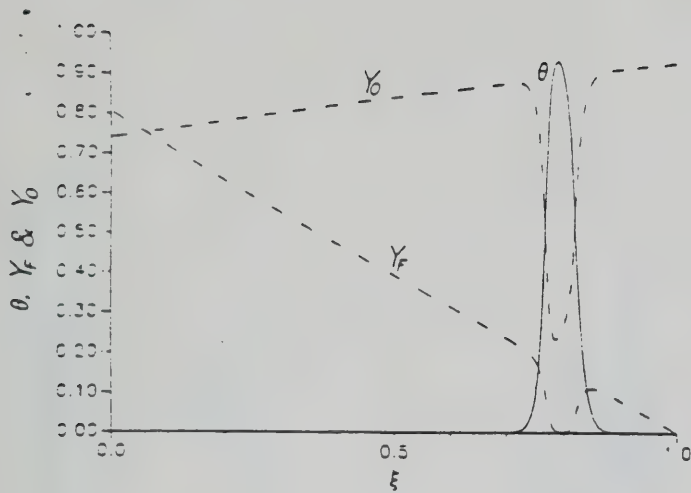
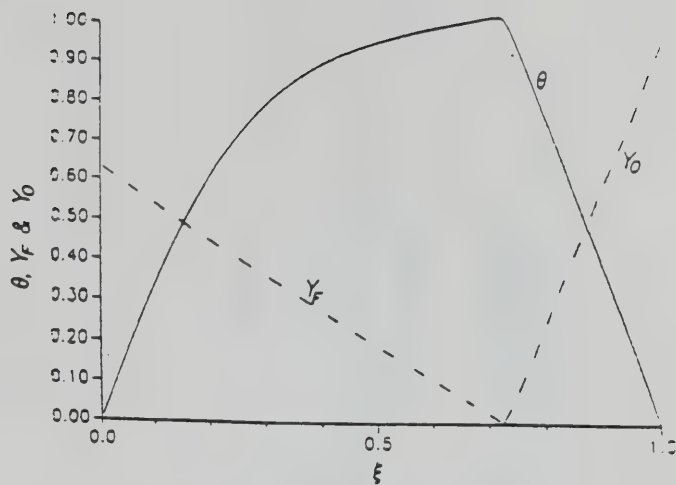


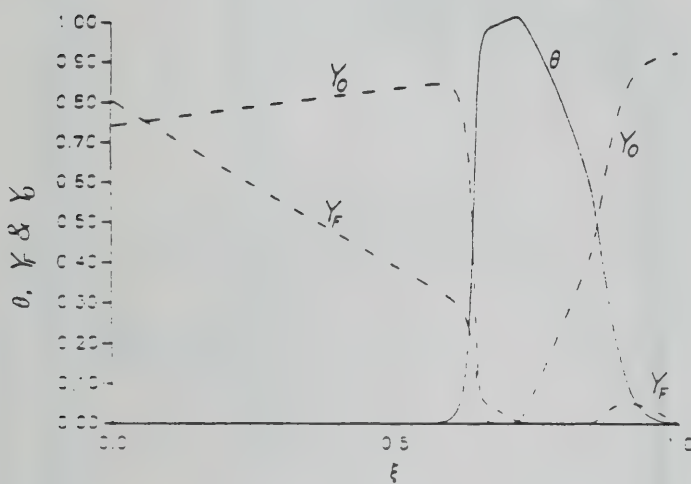
FIGURE 4. Computational grid.



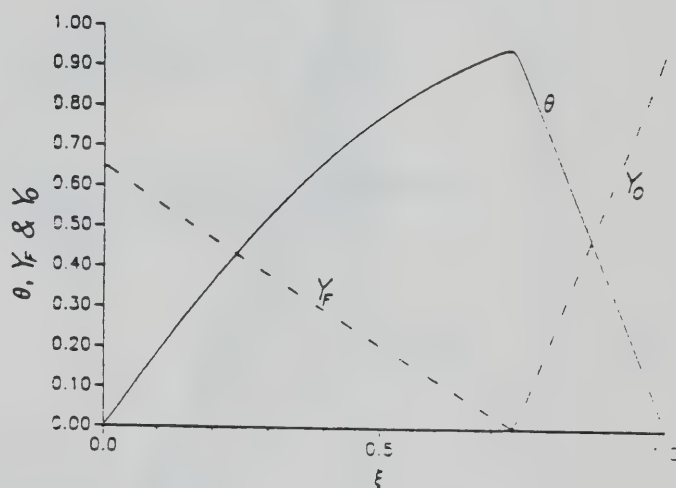
$t = 1.089 \text{ sec}$



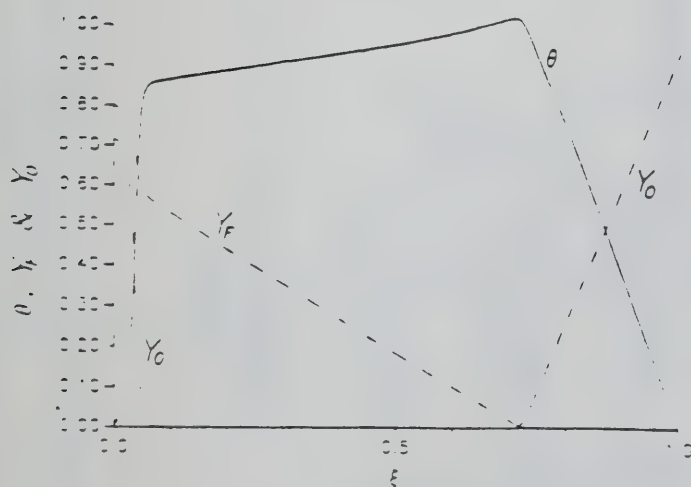
$t = 1.140 \text{ sec}$



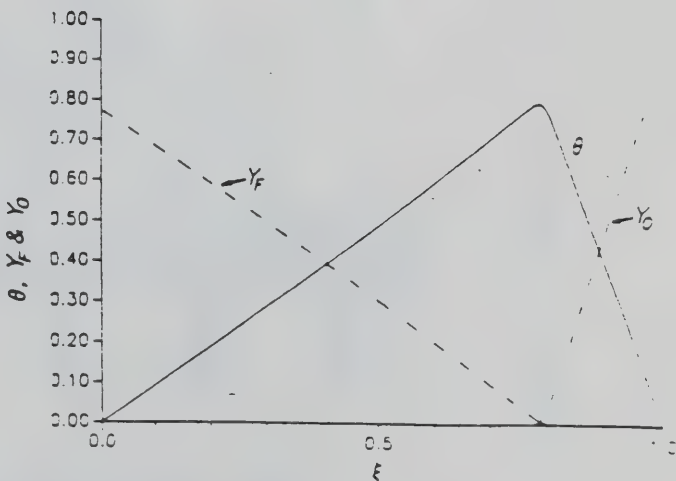
$t = 1.091 \text{ sec}$



$t = 1.240 \text{ sec}$



$t = 1.102 \text{ sec}$



$t = 3.887 \text{ sec}$

Figure 5. History of the piloted ignition process from ignition ($t=1.089 \text{ sec}$) to development of a steady diffusion flame ($t=3.887 \text{ sec}$). Note: the scales for Y_O & Y_F are not shown for clarity. They differ from the scale for θ by a constant factor which is 0.250 for Y_O & 0.167 for Y_F .

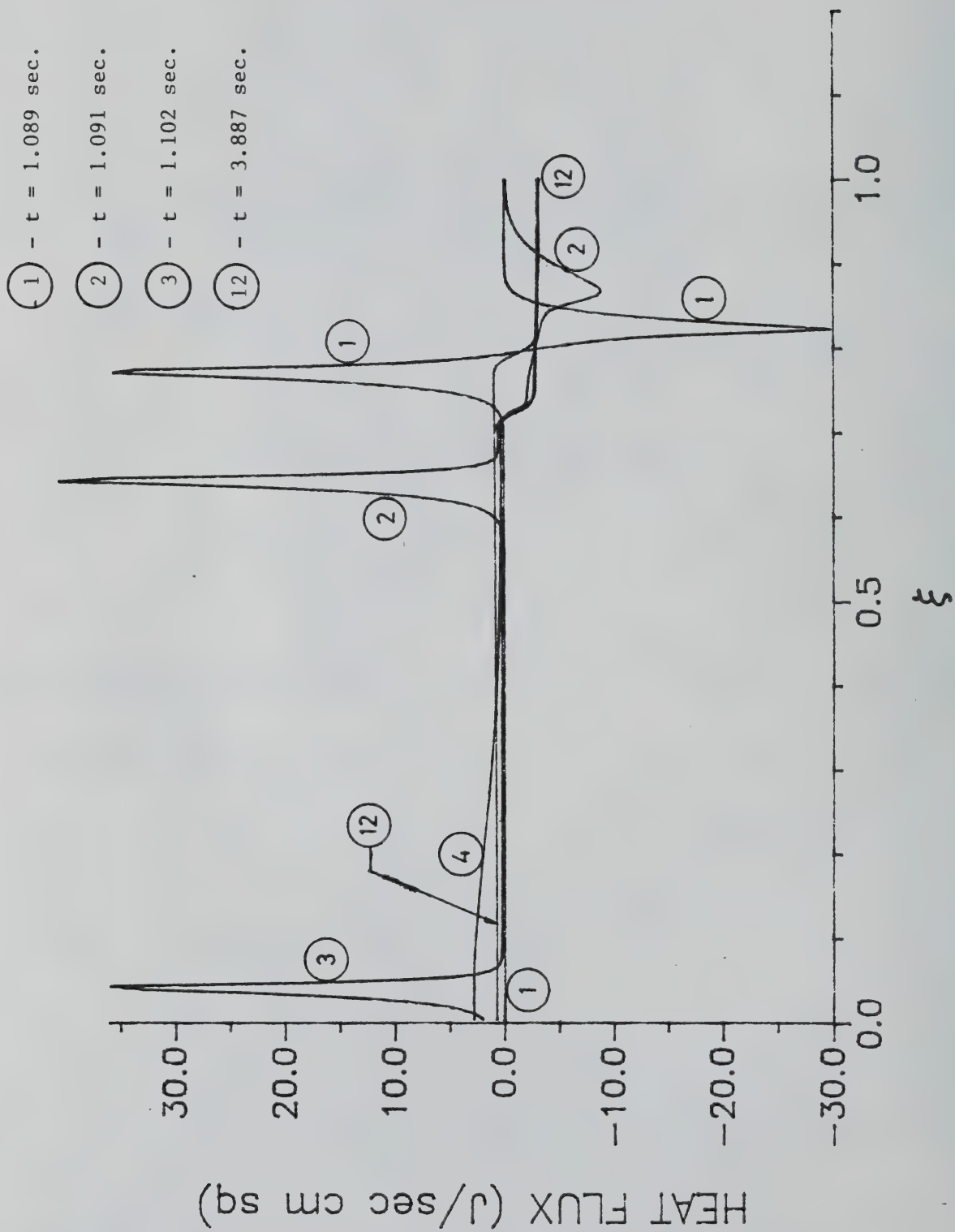


FIGURE 6: Heat flux profiles (proportional to temperature gradient) for the propagating pre-mixed flame during piloted ignition.

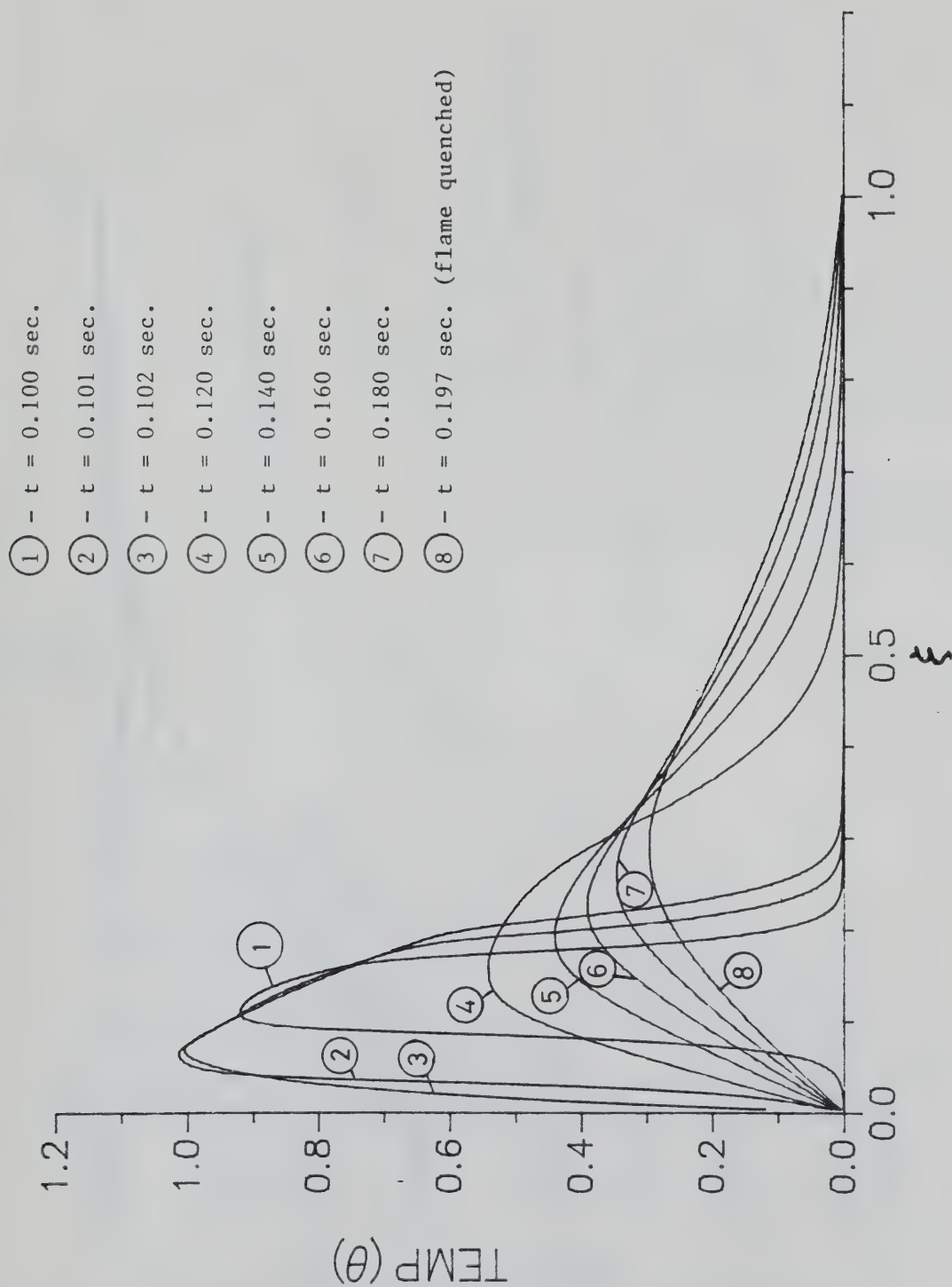


FIGURE 7: Temperature profiles for the quenched pre-mixed flame (resulting in a flash).

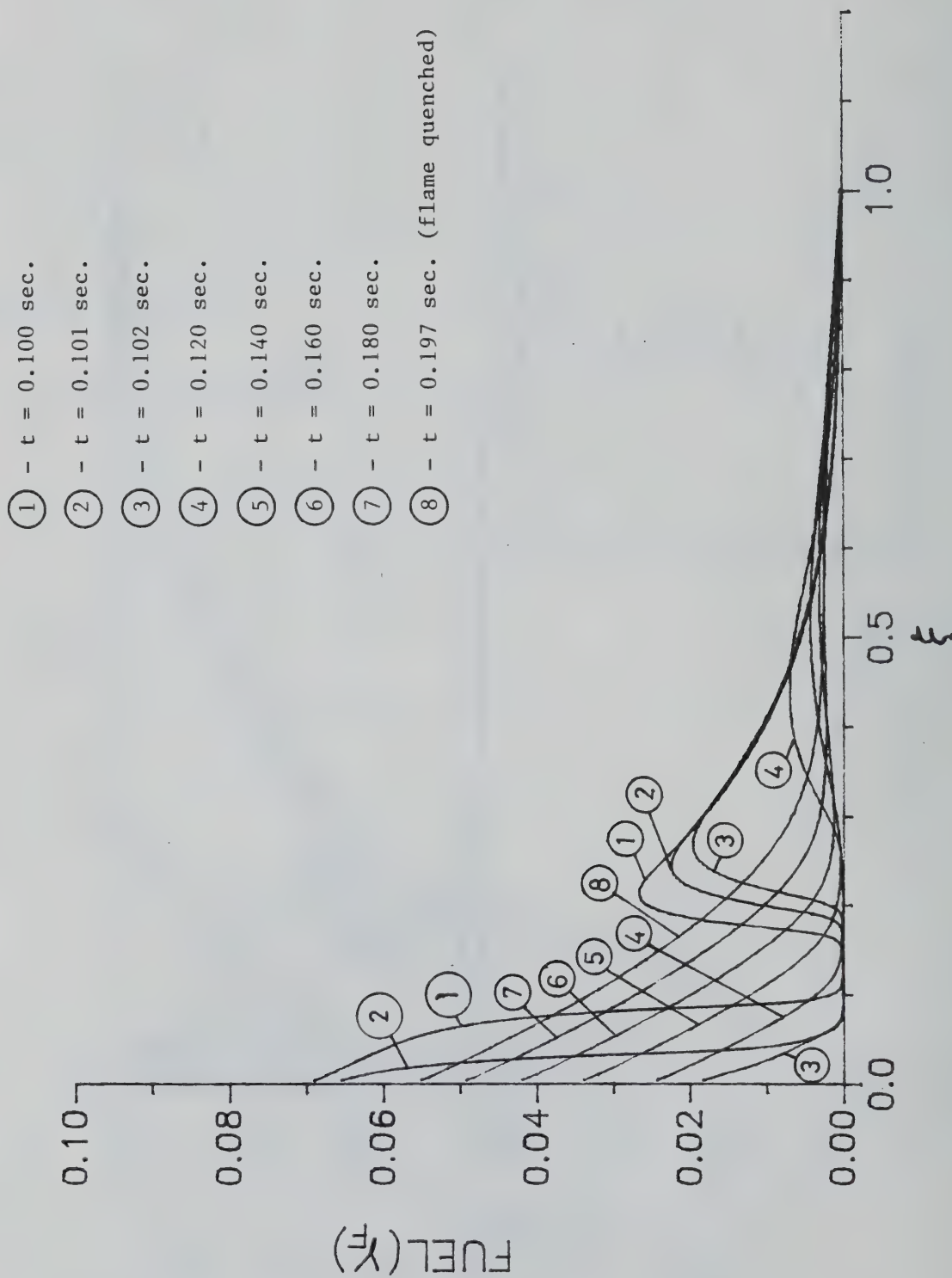


FIGURE 8: Fuel concentration profiles for the quenched pre-mixed flame (resulting in a flash)

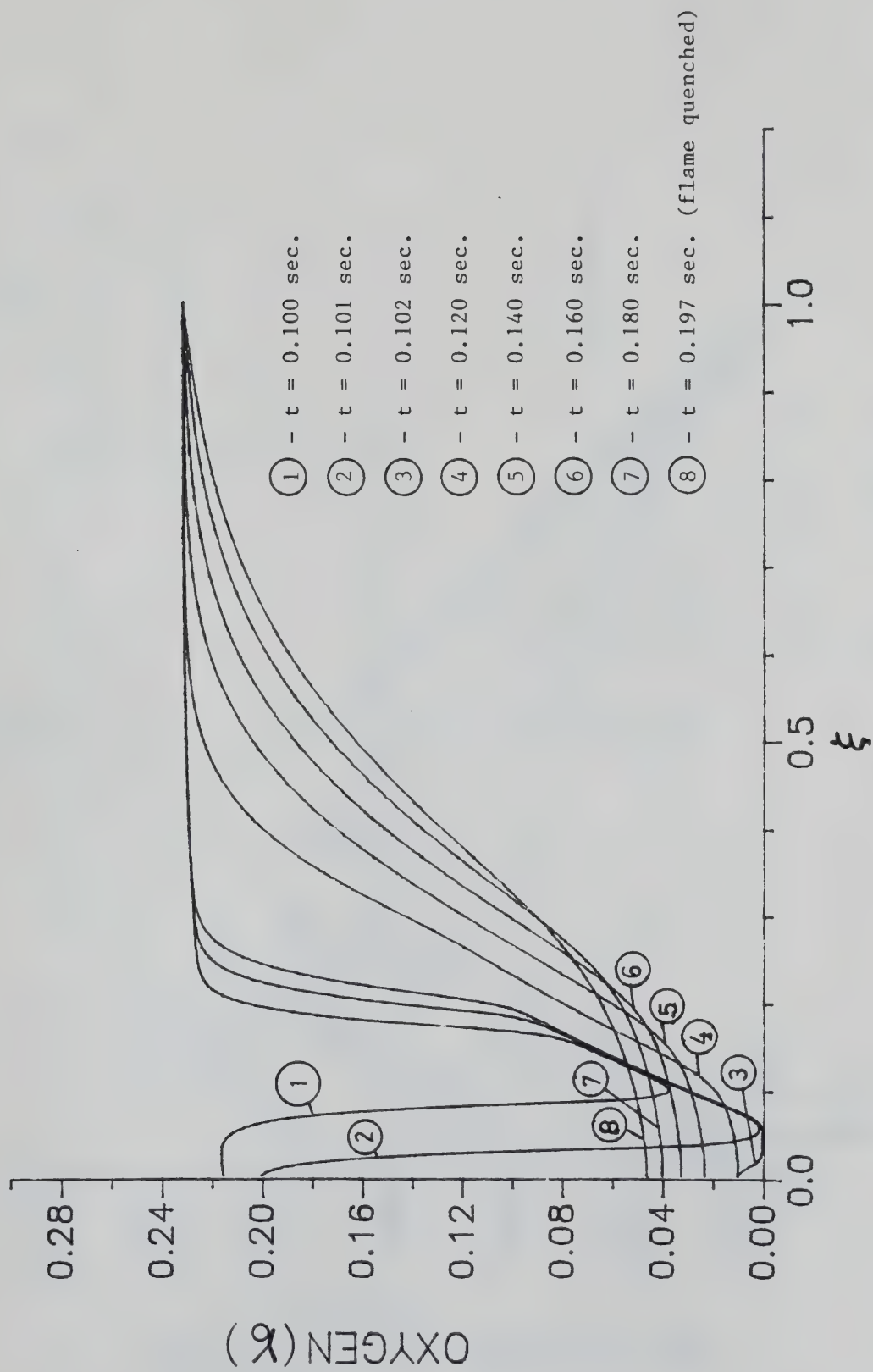


FIGURE 9: Oxygen concentration profiles for the quenched pre-mixed flame (resulting in a flash)

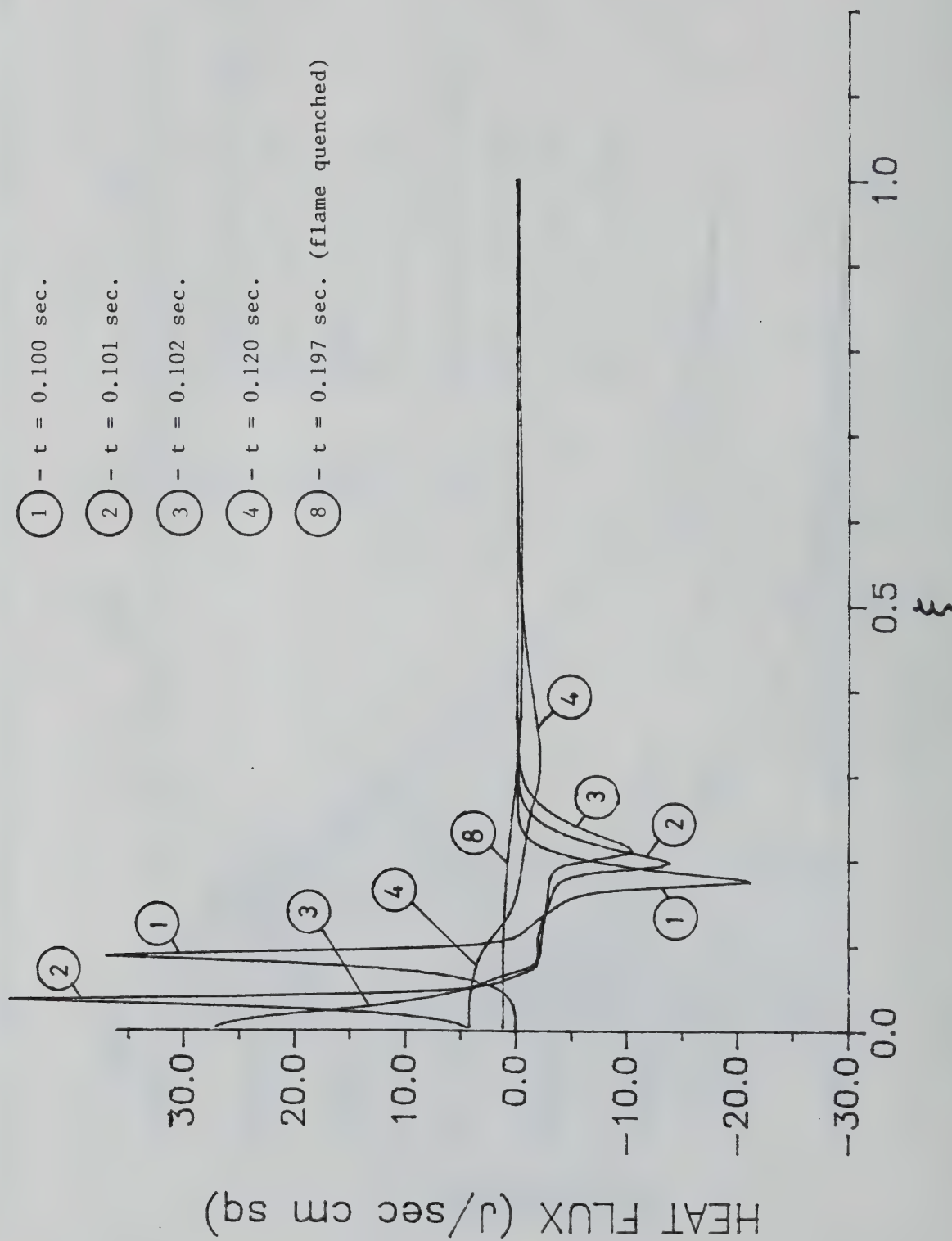


FIGURE 10: Heat flux profiles for the quenched pre-mixed flame (resulting in a flash)

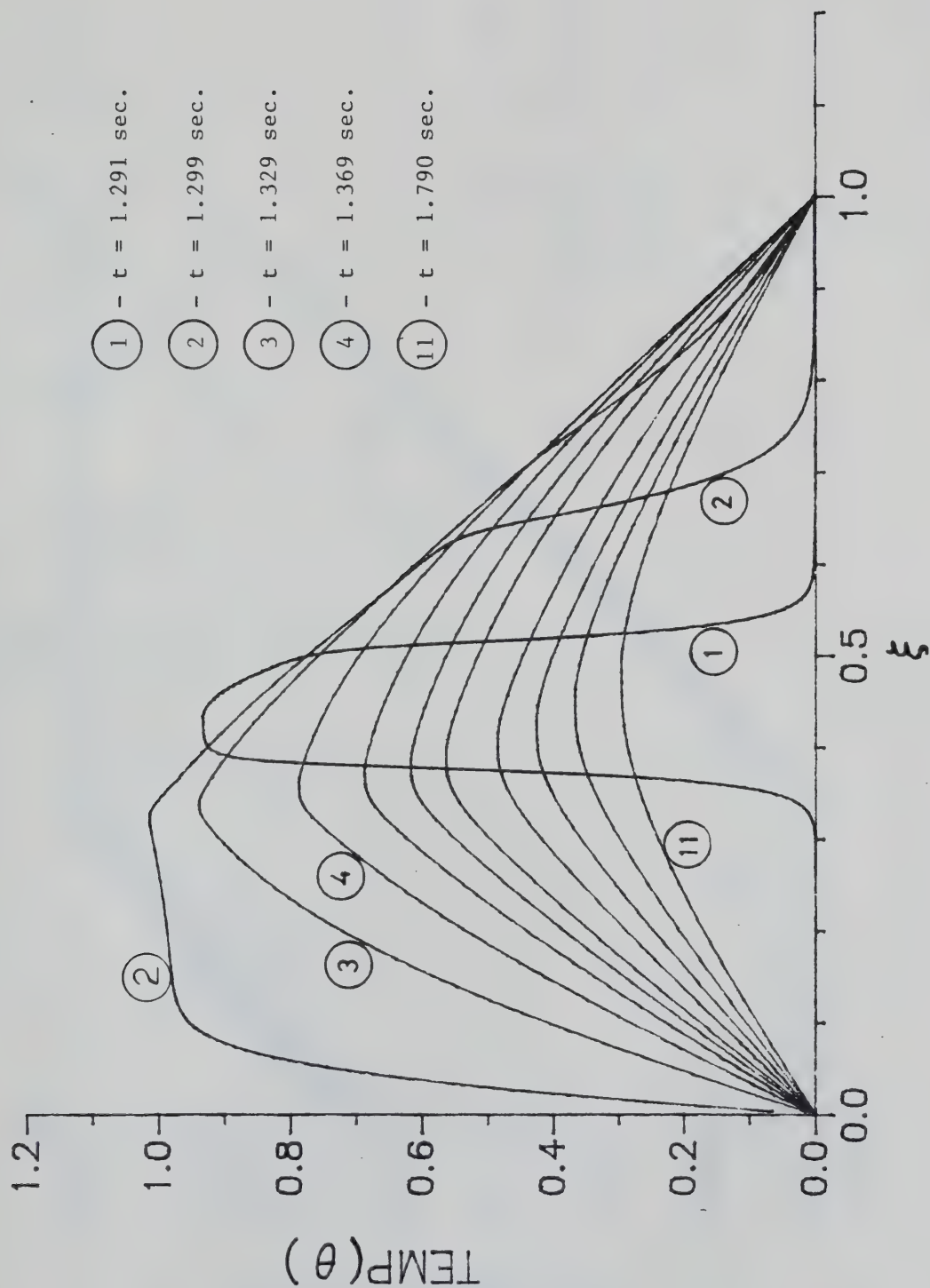


FIGURE 11: Temperature profiles during flashes caused by the fuel flow rate being below the lean flammability limit.

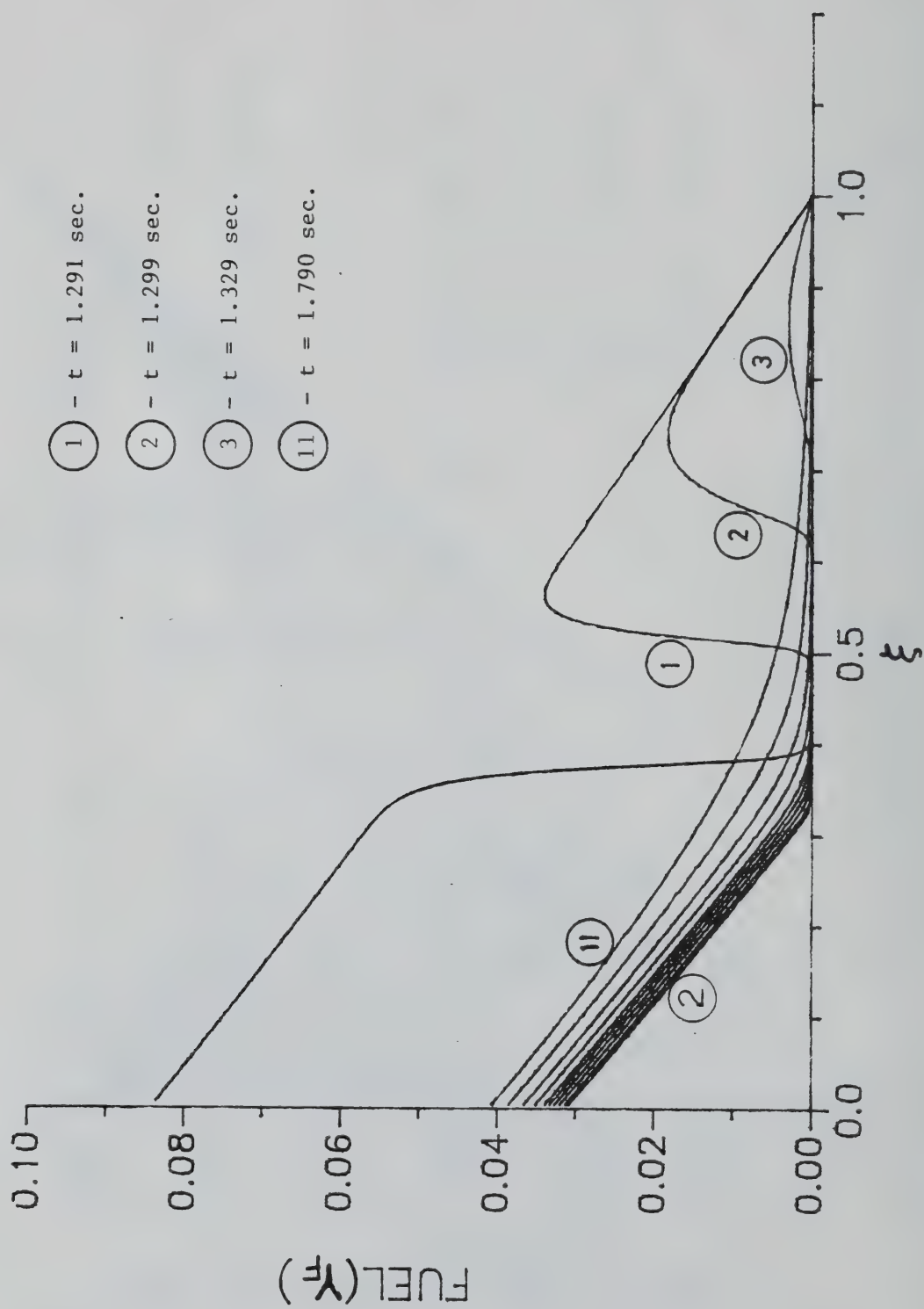


FIGURE 12: Fuel concentration profiles during flashes caused by the fuel flow rate being below the lean flammability limit.

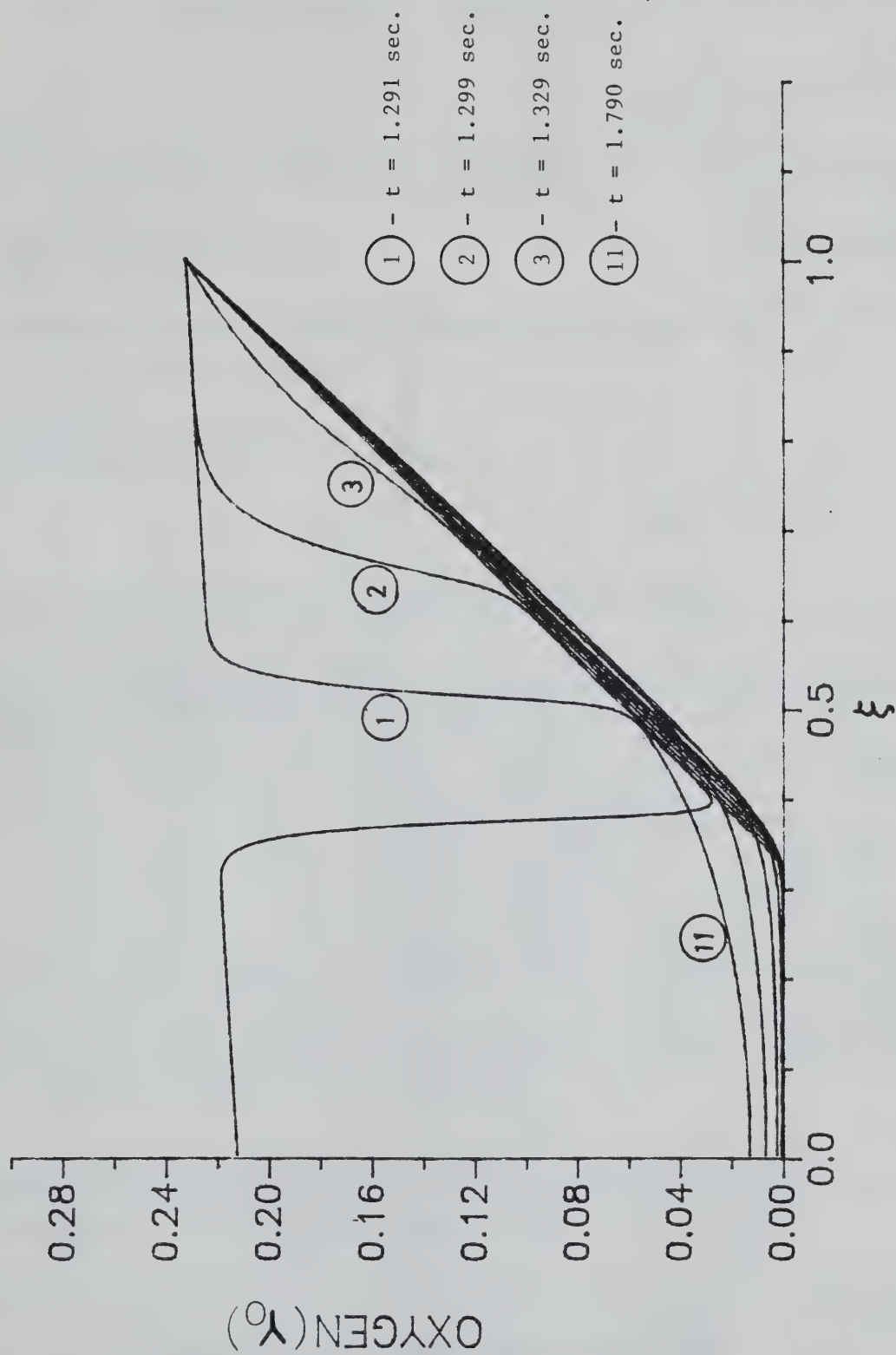


FIGURE 13: Oxygen concentration profiles during flashes caused by the fuel flow rate being below the lean flammability limit.

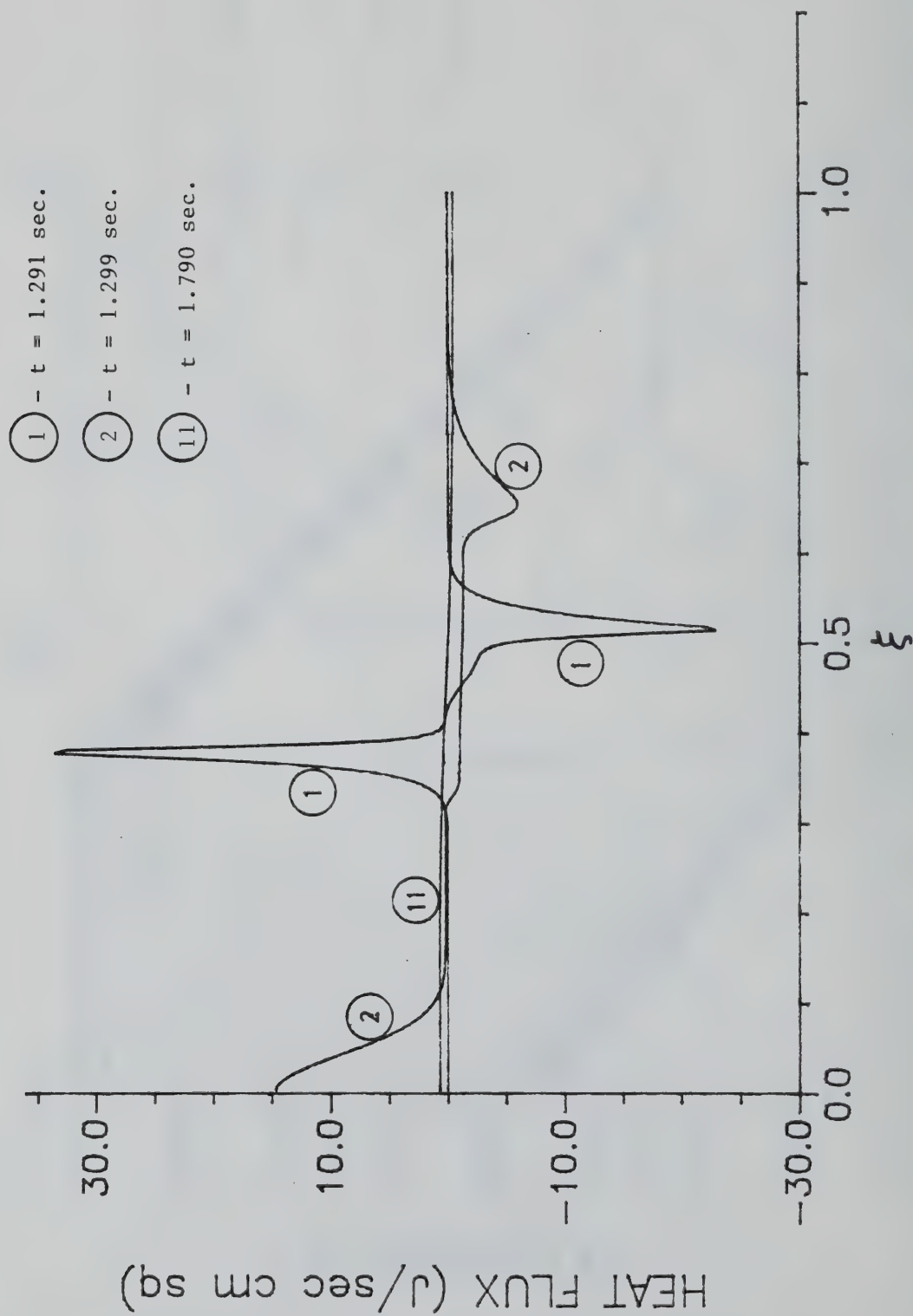


FIGURE 14: Heat flux profiles during flashes caused by the fuel flow rate being below the lean flammability limit.

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11. ABSTRACT <i>(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)</i> This paper presents a simple theoretical model of the piloted ignition process. The two-dimensional coupled solid and gas phase problem is simplified by assuming that the mass evolution rate from the combustible solid is a known function of time and by employing a plane rather than a point ignition source. These assumptions reduce the model problem to a transient one-dimensional analysis of the gas-phase phenomena. The model equations are solved numerically using a fast scheme especially suited to combustion problems. The pilot flame is modeled as a thin slab of gas that is periodically heated to the adiabatic flame temperature of the stoichiometric mixture. The effects of: (i) the location of the ignition source, (ii) the fuel mass evolution rate from the surface, and (iii) the surface temperature of the solid are investigated. This model adequately explains the pre-ignition flashes that are often observed experimentally. It also provides a rational criterion for positioning of the pilot flame. It is found that the minimum fuel flow rate, by itself is insufficient for predicting the onset of piloted ignition and that heat losses to the surface play an important role. Also, the conditions at extinction of a steady diffusion flame are found to be identical to those at piloted ignition.			
12. KEY WORDS <i>(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)</i> cellulosic materials; ignition; pilot flame			
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